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Electronic bicycle ergometer: a simple calibration procedure

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CLARK, J. H., AND J. E. GREENLEAF. *Electronic bicycle ergometer: a simple calibration procedure.* J. Appl. Physiol. 30(3): 440–442. 1971.—A description is given of a relatively simple technique for the direct calibration of an electronic ergometer. The procedure requires only standard shop and laboratory equipment: a machinist's lathe, a platform scale, an electronic counter/timer, and a strobe light. Construction of a separate drive assembly is not necessary. The ergometer was tested over a variety of operating conditions used in physiological experimentation. During tests at high work loads, appreciable calibration errors were encountered. Measurements of control circuit outputs indicated that these errors were the result of an uncompensated decrease in output torque as temperature increased in the eddy current brake used as the ergometer load device.

work-load calibration

THE BICYCLE ERGOMETER is one of the basic instruments in many laboratories of applied physiology. Many experimenters use their electronic bicycles with only the manufacturers' original work-load calibrations. Some occasionally calibrate their machines indirectly with other mechanically calibrated bicycles (3). The usual procedure for direct calibration (1, 2) requires special equipment often not available in many instrument calibration laboratories. This report describes a relatively simple method for the direct calibration of an electronic ergometer. Results of the calibration are discussed and suggestions are made for minimizing load errors.

This ergometer uses as a load device an eddy current brake in which a solid armature, connected through gearing to the pedals, is rotated in a magnetic field (Fig. 1). This unit is normally enclosed in a nonvented steel case. With varying pedal speed, the work rate (power load) is kept constant by a feedback voltage controlled by pulses from a tachometer generator on the armature shaft. The tachometer pulses are electronically integrated to produce a voltage proportional to pedal speed. This voltage, in conjunction with that of the load selector, controls the current in the field coils of the eddy current brake. The magnitude of this current controls the strength of the magnetic field in which the armature is rotating and thus controls the drag force applied to the armature and thence to the pedals. The drag force on the pedals changes inversely with pedaling speed from 6 to 16 rad/s (60 to 150 rpm) and the power load of the ergometer is designed to remain constant at the level set by the load selector.

PROCEDURE

The pedal arms and bicycle framework were removed and the operating parts of the ergometer were assembled in the shop area. A 16-inch machinist's lathe was used as a source of controlled mechanical power to drive the ergometer. The ergometer pedal shaft was locked into the lathe chuck, leaving the pedal housing free to pivot about the pedal shaft. A length of stock aluminum channel was attached to the pedal housing and its free end positioned on the platform balance (Shadowgraph model 4174). The height of the balance was adjusted so that its reaction point (center of weight pan) was level with the pedal shaft and at a measured distance from it at the balanced position. Weight was added to the tare pan to equal the force on the reaction point from the weight of the pedal-brake assembly. Prior to and during each test a strobe light (General Radio Strobotac type 1531-A) was utilized to measure the angular rate of the pedal shaft (lathe speed) and to calibrate the pedaling rate (rpm) indicator on the ergometer control box (Fig. 2) For ease in viewing, the period of rotation of the pedal shaft was measured with the strobe light aimed at the key on the end of the brake shaft. The turning ratio of the eddy current brake shaft to the pedal shaft was 16:1. To increase accuracy, the period of the strobe flashes was measured with an electronic counter/timer (Monsanto model 1000). As the pedal shaft was driven at a constant rate the drag force of the brake imparted a torque about this shaft to the pedal-brake assembly. Measurements of this torque and the shaft speed were used to derive the true power load being produced by the ergometer.

The load calibration procedure is as follows. *a*) Select a load value (P)[1] and a pedaling rate (N):

$$P = 100 \text{ W } (100 \text{ N-m/s}) \ (611.8 \text{ kg-m/s})$$

$$N = 6.28 \text{ rad/s } (60 \text{ rpm})$$

b) Determine the required pedal shaft torque (T):

$$T_{N\text{-}m} = \frac{P_W}{N_{rad/s}} = \frac{100}{6.28}$$

$$= 15.915 \text{ N-m } (1.623 \text{ kgf-m}) \ (11.739 \text{ ft-lbf})$$

c) Measure the lever arm (D) between the pedal shaft axis and the reaction point at the center of the balance pan:

$$D = 0.914 \text{ m } (3.00 \text{ ft})$$

d) Then calculate the force (F) exerted at the reaction point on the balance by the computed torque (T):

$$F = \frac{T_{N\text{-}m}}{D_m} = \frac{15.915 \text{ N-m}}{0.914 \text{ m}} = 17.4 \text{ N } (1.77 \text{ kg}) \ (3.91 \text{ lb})$$

e) Add to the tare side of the balance a weight equivalent to the calculated reaction force (F):

$$F = 1.77 \text{ kg } (3.91 \text{ lb})$$

f) Set lathe speed (previously calibrated with the strobe light) to the selected pedal speed:

$$N = 6.28 \text{ rad/s } (60 \text{ rpm})$$

g) Adjust the ergometer load selector until the balance comes to the balance point. *h*) Read and record the position of the ergometer load indicator. *i*) Determine the ergometer error (E) by sub-

[1] P watts = $T_{N\text{-}m} \times N$ rad/s; $T_{N\text{-}m}$ = 0.10197 kgf-m (0.7376 ft-lbf).

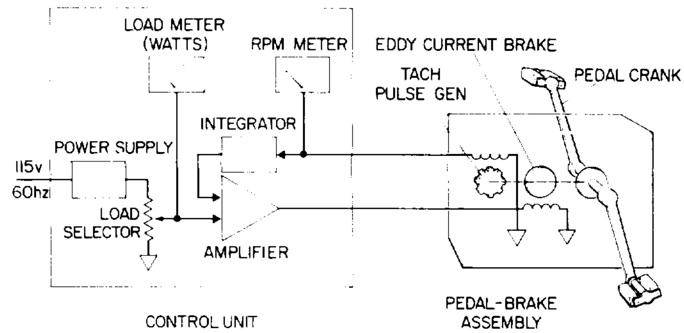

FIG. 1. Electronic ergometer; functional diagram.

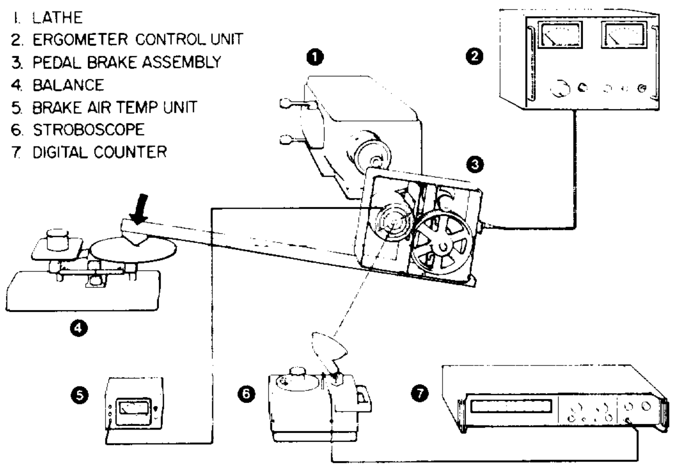

FIG. 2. Ergometer calibration setup: (*1*) lathe, (*2*) ergometer control unit, (*3*) pedal-brake assembly, (*4*) balance, (*5*) brake-air temperature unit, (*6*) stroboscope, (*7*) digital counter.

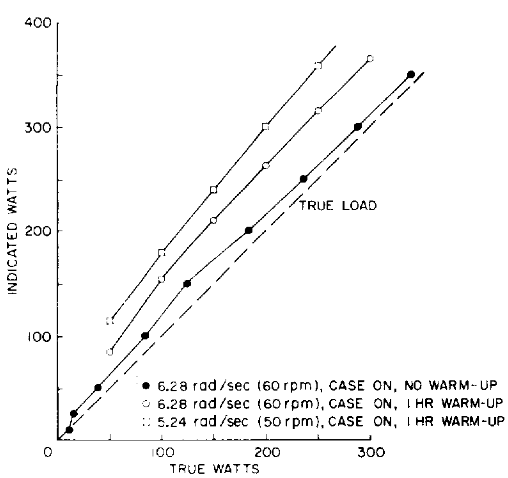

FIG. 3. Typical load calibrations. ● 6.28 rad/s (60 rpm), case on, no warm-up. ○ 6.28 rad/s (60 rpm), case on, 1-hr warm-up. □ 5.24 rad/s (50 rpm), case on, 1-hr warm-up. Dash line shows true load.

tracting the true power load (P_t) from the indicated power load (P_i):

$$E \text{ watts} = (P_i - P_t)$$

During the load calibration when brake heating became evident, a thermistor probe (Yellow Springs Instruments model 409) was positioned in the exit airstream of the brake housing to monitor brake exit air temperature (Fig. 2).

RESULTS OF CALIBRATION

A typical calibration curve (Fig. 3) was run at 6.28 rad/s (60 rpm), with the steel case in place on the brake unit (no warm-up), beginning with the lowest load and remaining at each load for about 1 min. The increase in temperature of the ergometer housing was minimal. Two additional calibration curves at pedal speeds of 5.24 and 6.28 rad/s (50 and 60 rpm) are shown in Fig. 3. Each of these was preceded by 1 hr of warm-up at an indicated load of 250 W. These curves will apply only as long as the brake temperature remains at the level reached during the warm-up.

For the next run, a true load of 250 W was applied to the ergometer at 5.24 rad/s (50 rpm), case on, for a period of 1 hr (Fig. 4). The housing temperature and the indicator error increased severely. After 55 min the steel casing was almost too hot to touch, the load selector was at its maximal travel, and the indicator read 397 W. Beyond this point the ergometer could no longer maintain a true load of 250 W. When the ergometer had cooled to room temperature, the steel case was removed from the pedal-brake assembly and another 1-hr run was made at 250 W and 5.24 rad/s. The increase in indicator error was somewhat less severe during this run, and equilibrium was reached at 320 W indicated

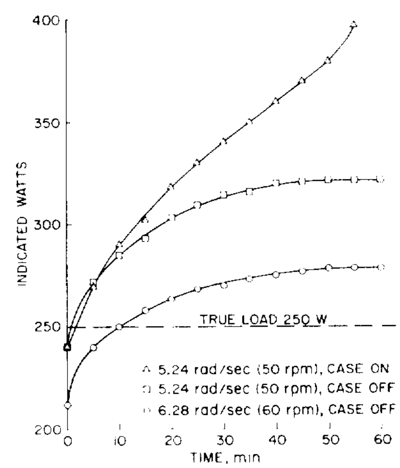

FIG. 4. Error change during warm-up at constant true load of 250 W. △ 5.24 rad/s (50 rpm), case on. □ 5.24 rad/s (50 rpm), case off. ○ 6.28 rad/s (60 rpm), case off.

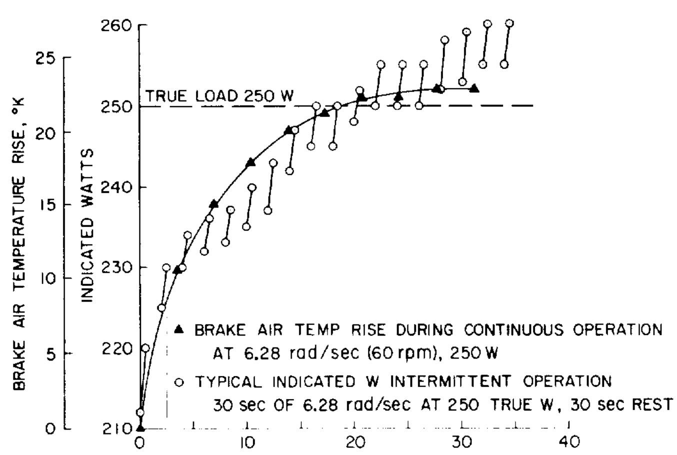

FIG. 5. ▲ (*outer ordinate scale*). Brake exit air temperature vs. running time. ○ (*inner ordinate scale*). Indicated watts vs. elapsed time during intermittent operation with 30 s of 250 W true load at 60 rpm alternated with 30 s of rest. (For clarity, only every other work cycle is shown.)

in 50 min. When the ergometer had again cooled to room temperature, another run was made at the same load with the pedal speed increased to 6.28 rad/s. The higher speed increased the flow of air through the cooling fins on the brake and further improved ergometer performance, so that equilibrium, at an indicated load of 278 W, was reached in 50 min (Fig. 4). The results from Fig. 4 clearly indicate the difficulty in using the load indicator of this ergometer for maintaining accurate high work loads during continuous operation in tests lasting up to 1 hr. Brake temperature equilibrium is established when the ergometer, without its casing, is operated at constant high loads for longer than 1 hr. A constant correction can then be applied to the load indicator.

The temperature rise in the airflow was monitored while the previous run of 250 W at 6.28 rad/s was repeated. The brake air temperature reached equilibrium after a rise of 23° K above the ambient air temperature in 40 min (Fig. 5, outer ordinate scale).

Intermittent ergometer operation was also included in this test schedule. The manner in which ergometer error changes during such a run is shown in Fig. 5. In this example, 30 s of 6.28-rad/s (60-rpm) pedaling at 250 W true load is alternated with 30 s of rest for the duration of the run. Every other work cycle is omitted from the plot for greater clarity. The end points of the line segments show the indicated loads at the beginning and end of individual work cycles. The average values for indicated load follow a curve similar to that for 6.28-rad/s (60-rpm) continuous operation (Fig. 3) but level off at a lower load error. The rate at which the load indication changes during each work cycle does not vary much throughout the run and is similar to that of the first 30 s of the 6.28-rad/s curve in Fig. 3.

To obtain further data on the effects of brake temperature variations upon the accuracy of this ergometer, a special test was made later in which the brake control coil voltage and current were monitored while the ergometer was pedaled at a constant speed with a fixed (200 W) setting of the load control. Brake temperature increased and true torque decreased as before but no variations were detected in either the voltage or current in the brake coil.

CONCLUSIONS

Measurements made during and after the calibration of this ergometer support the following observations. *1)* On short runs at low work loads, ergometer errors of about +4% of full-scale work load can be expected. *2)* On long runs at high loads, errors in excess of +100 W and greater than +50% of true load can occur with a considerable rise in brake temperature. *3)* The ergometer load error increases as brake temperature increases. *4)* Brake temperature increases as brake torque is increased when the ergometer work load is increased at a given pedal speed or when pedal speed is decreased at a given work load. *5)* During constant speed operation at any fixed load control setting, the brake control coil voltage and current remain constant; but brake torque decreases as brake temperature increases.

The ergometer load indicator is actuated by the brake control current, but true ergometer work load is a direct function of brake torque. Therefore, the large errors encountered during this calibration are the result of a decrease in the ratio of brake torque to control current as brake temperature increases.

The brake used in this ergometer is an air-cooled eddy current brake with a continuous power rating that is ample for all loads within the range of the ergometer. To operate at this rating, the brake must be provided with adequate cooling to remove the heat it generates. The location of this brake within the nonvented casing of the ergometer pedaling unit severely restricts its capacity for heat dissipation. The resulting temperature effect on brake torque produces gross load errors and reduces the load capacity of the ergometer.

The most obvious and easily accomplished solution to this problem would be to increase the flow of cooling air through the brake by ventilating the case, removing the case, or adding external equipment to increase the velocity and/or reduce the temperature of the cooling air. Simple techniques for improving brake heat dissipation should be capable of eliminating a major portion of the load error in this ergometer.

Even with good cooling, small changes in brake temperature will probably occur. This smaller source of load error might be nullified by the addition of a temperature feedback circuit to modify brake control current in compensation to the effect of small variations in brake temperature. This might be more practically applied to the design of a new ergometer than to the modification of an existing one.

The large errors encountered during this calibration help to emphasize the importance of calibrating this type of equipment prior to its use. The technique described in this paper can be adapted to the calibration of other types of ergometers. The procedure is an alternative method of direct ergometer calibration to local measurement standards without a specially built drive assembly.

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